MANTLE RAYLEIGH WAVES FROM THE KAMCHATKA EARTHQUAKE OF NOVEMBER 4, 1952*

By MAURICE EWING and FRANK PRESS

ABSTRACT

Mantle Rayleigh waves from the Kamchatka earthquake of November 4, 1952, are analyzed. The new Palisades long-period vertical seismograph recorded orders R_6–R_{15}, the corresponding paths involving up to seven complete passages around the earth. The dispersion data for periods below 400 sec. are in excellent agreement with earlier results and can be explained in terms of the known increase of shear velocity with depth in the mantle. Data for periods 400–480 sec. indicate a tendency for the group velocity curve to level off, suggesting that these long waves are influenced by a low or vanishing shear velocity in the core. Deduction of internal friction in the mantle from wave absorption gives a value $1/Q = 370 \times 10^{-5}$ for periods 250–350 sec. This is a little over half the value reported earlier for periods 140–215 sec.

INTRODUCTION

IN A PREVIOUS paper[1] an investigation of amplitudes and dispersion of mantle Rayleigh waves was presented, using data from three earthquakes recorded on the Pasadena linear strain and Benioff seismographs. Rayleigh waves in the period range 1–7 minutes involving paths with as many as three circuits of the earth (R_2–R_7) were described. Orbital motion of a surface particle proper for Rayleigh waves was demonstrated, a group velocity curve of high precision was deduced from the seismograms, and a theory was presented which accounted for the properties of these waves in terms of mantle structure. The observed group velocity curve showed a minimum value of 3.54 km/sec. at a period of 225 sec. Analysis of the amplitudes led to values of internal friction in the mantle for periods of 140 and 215 sec.

Stoneley[2] made an approximate calculation for the dispersion of Rayleigh waves in the period range which is treated in the present paper. His calculations were made in an investigation of the effect of the "20° discontinuity" upon surface waves. He represented the mantle as a 480-km. layer with the shear velocity $\beta_1 = 4.7$ km/sec. and the density $\rho_1 = 3.5$ gm/cm.^{3} over a substratum with $\beta_2 = 5.66$ km/sec. and $\rho_2 = 4.11$ gm/cm.^{3} His approximate calculations gave a minimum value of group velocity of 4.0 km/sec. at a period of 167 sec. Using a rough estimate of the correction which his approximation requires, he concludes that the minimum of group velocity would be at a period of about 4 minutes, which is remarkably near the value now observed. Stoneley drew attention to the valuable data from observations on these waves which could be collected if a suitable long-period seismograph were available.

Our theoretical treatment of the dispersion curve involves an exact calculation

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[1] Maurice Ewing and Frank Press, "An Investigation of Mantle Rayleigh Waves," *Bull. Seism. Soc. Am.*, 44: 127–147 (1954).

[2] Robert Stoneley, "Surface Waves Associated with the 20° Discontinuity." *Mon. Not. Roy. Astron. Soc., Geophys. Suppl.*, pp. 39–43, 1937.

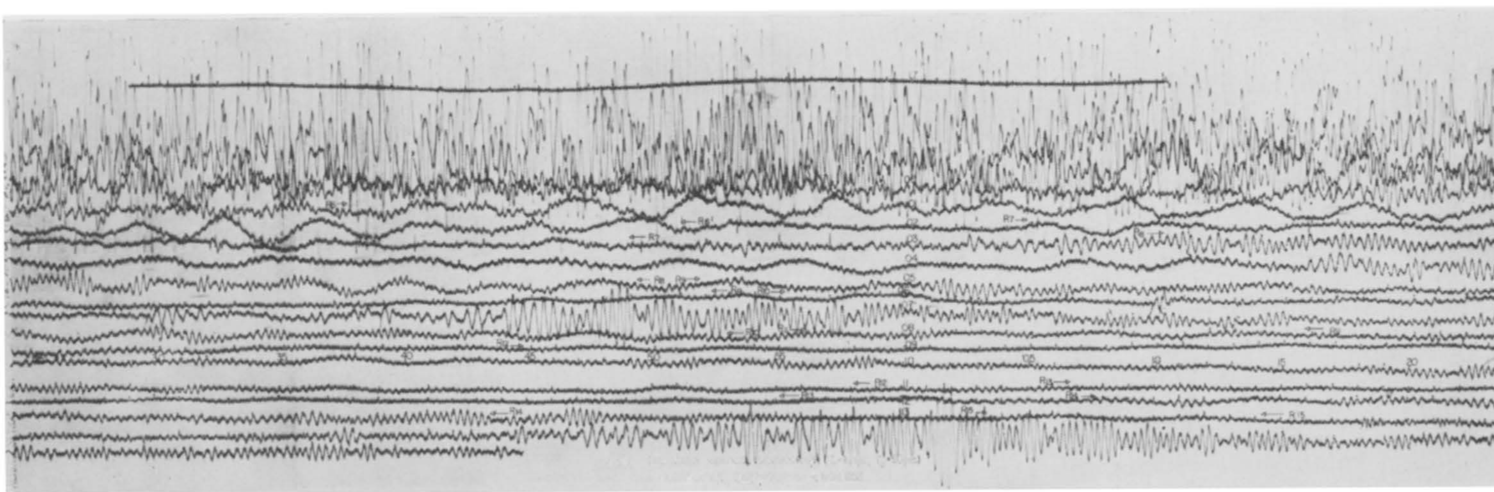

Fig. 1. Palisades vertical seismograph (T_0 = 15 sec., T_g = 90 sec.), Kamchatka earthquake, November 4, 1952.

for a layer 516 km. thick with $\beta_1 = 4.48$ km/sec. over a substratum with $\beta_2 = 6.15$ km/sec. and density 10/9 times greater than that in the layer. As stated in our first paper on the mantle Rayleigh waves, we do not intend that our calculation shall imply belief in the reality of layering at approximately 500 km. depth. We consider the steplike velocity-depth relation simply as an approximation to the actual gradual increase of velocity with depth.

A little over a year ago a special long-period vertical seismograph ($T_0 = 15$ sec., $T_g = 90$ sec.) was put in operation at Palisades for the purpose of recording mantle Rayleigh waves and other long-period oscillations. The instrument was quite sensitive, allowing for operation with overdamped pendulum and galvanometer, yet with sufficient magnification to record at the limit of sensitivity imposed by microseisms. Response to long-period oscillations was improved in this way. It was found necessary to maintain the instrument at constant temperature as well as to provide buoyancy compensation for the pendulum so that spurious oscillations originating in atmospheric pressure fluctuations[3] could be removed. A more complete report on the seismograph will be presented separately.

On November 4, 1952, a large earthquake occurred on Kamchatka. B.C.I.S. gives for epicentral data 52°9 N, 160°1 E, $H = 16^h\ 58^m\ 23^s$ and Pasadena magnitude 8¼. The Palisades instrument recorded mantle Rayleigh waves of orders R_6-R_{15}, the corresponding paths involving as many as seven complete passages around the earth. Earlier orders were off scale and could not be read. The Pasadena linear strain seismograph wrote an excellent record of R_1, R_2, and R_4. These long-period oscillations, continuing for more than twenty hours after the instant of the shock, could be positively identified with the proper order of mantle Rayleigh wave by use of the dispersion curve derived in the earlier paper.[4]

The new data presented in this paper are highly significant in that they extend the observed propagation distances of mantle Rayleigh waves to 288,370 km., provide additional points for the group velocity curve with a suggestion that the trend of the curve for periods longer than 400 sec. is influenced by the core, and supply an additional value for the internal friction of mantle rocks for periods 250–350 sec.

Data

The Palisades long-period vertical seismogram is reproduced in figure 1. Various orders of mantle Rayleigh waves are indicated by arrows. The short-period crustal Rayleigh waves from the numerous aftershocks often occur riding on the longer-period mantle oscillations of the main shock, making record reading difficult at these times.

The method of analysis is similar to that described in detail in the previous paper[5] and only the results will be given here.

Table 1 lists arrival times, travel times, and velocities for the different periods observed in each order of mantle Rayleigh waves. The results are presented graph-

[3] Maurice Ewing and Frank Press, "Further Study of Atmospheric Pressure Fluctuations Recorded on Seismographs," *Trans. Am. Geophys. Union, 34*: 95–100 (1953).

[4] See footnote 1.

[5] See footnote 1.

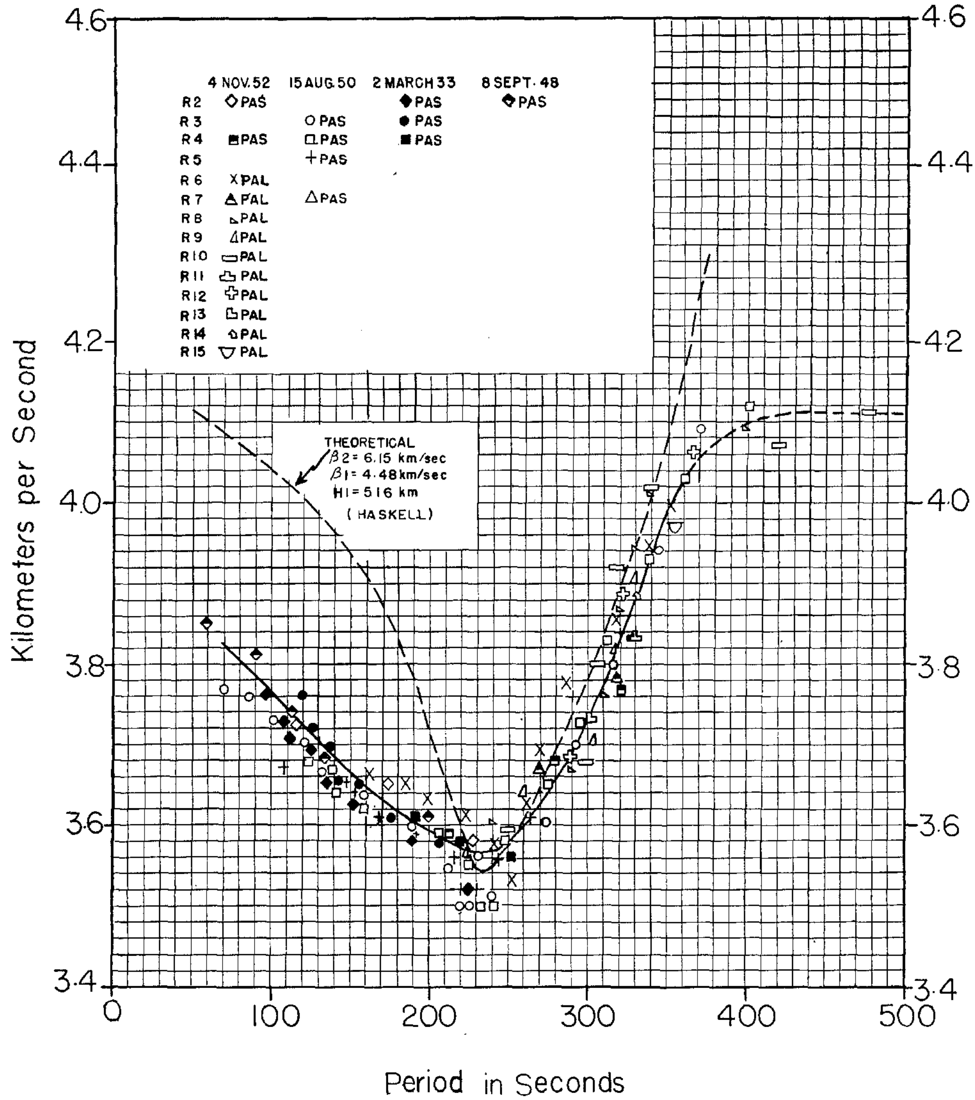

Fig. 2. Observed group velocity for mantle Rayleigh waves, compared to theoretical curve based on single-layer approximation.

ically in figure 2, where group velocity is plotted as a function of period. Data from our previous paper are included. It can be seen in figures 1 and 2 that only R_6 exhibits both the long-period and the short-period branch, which represent, respectively, trains of waves the periods of which decrease and increase with time, the two trains merging finally in the Airy phase at the minimum value of group velocity. Although the short-period branch of R_2 alone is listed, there is a slight but definite indication of a long wave on the Pasadena seismogram. Accurate reading of the period is made difficult by the insufficient separation of the long waves at this short

TABLE 1

DISPERSION DATA, NOVEMBER 4, 1952

Arrival time*	Period (sec.)	Travel time (h. m. s.)	Travel time (sec.)	Velocity (km/sec.)
R_2 (Pasadena) Δ_2 = 33,450 km.				
19:28:10	112	02:30:02	9002	3.72
19:31:00	175	02:32:52	9172	3.65
19:34:20	225	02:36:12	9372	3.57
R_4 (Pasadena) Δ_4 = 73,450 km.				
22:22:40	320	05:24:32	19472	3.77
22:30:20	280	05:32:12	19932	3.68
22:38:20	220	05:40:12	20412	3.60
R_6 (Palisades) Δ_6 = 111,600 km.				
00:43:00	352	07:44:40	27880	4.00
00:51:00	340	07:52:40	28360	3.94
01:01:00	317	08:02:40	28960	3.85
01:11:00	285	08:12:40	29560	3.78
01:22:00	270	08:23:40	30220	3.69
01:33:00	262	08:34:40	30880	3.61
01:45:00	253	08:46:40	31600	3.53
01:37:00	245	08:38:40	31120	3.59
01:34:00	225	08:35:40	30940	3.61
01:31:00	200	08:32:40	30760	3.63
01:28:20	184	08:30:00	30600	3.65
01:26:00	160	08:27:40	30460	3.66
R_7 (Palisades) Δ_7 = 128,380 km.				
02:21:20	320	09:23:00	33780	3.80
02:41:00	270	09:42:40	34960	3.67
R_8 (Palisades) Δ_8 = 151,600 km.				
03:16:40	400	10:18:20	37100	4.09
03:28:00	340	10:29:40	37780	4.01
03:40:00	330	10:41:40	38500	3.94
03:54:00	320	10:55:40	39340	3.85
04:10:00	310	11:11:40	40300	3.76
04:26:00	290	11:27:40	41260	3.67
04:41:00	240	11:42:40	42160	3.60
R_9 (Palisades) Δ_9 = 168,370 km.				
04:52:40	335	11:54:20	42860	3.93
05:15:00	315	12:16:40	44200	3.81
05:38:00	305	12:39:40	45580	3.70
05:49:20	260	12:51:00	46260	3.64

* Clock corrections omitted: Pasadena + 15 sec.; Palisades + 3 sec.

TABLE 1—*Continued*

R_{10} (Palisades) Δ_{10} = 191,590 km.				
05:55:00	480	12:56:40	46600	4.11
06:02:00	420	13:03:40	47020	4.07
06:12:00	340	13:13:40	47620	4.02
06:32:20	320	13:34:00	48840	3.92
07:02:00	315	14:03:40	50620	3.78
07:28:00	290	14:29:40	52180	3.67
07:47:20	250	14:49:00	53340	3.59
R_{11} (Palisades) Δ_{11} = 208,370 km.				
08:06:00	330	15:07:40	54460	3.83
R_{12} (Palisades) Δ_{12} = 231,590 km.				
08:49:00	365	15:50:40	57040	4.06
09:30:00	320	16:31:40	59500	3.89
10:30:20	290	17:32:00	63120	3.67
R_{13} (Palisades) Δ_{13} = 248,370 km.				
11:28:20	300	18:30:00	66600	3.73
R_{14} (Palisades) Δ_{14} = 271,590 km.				
12:26:00	330	19:27:40	70060	3.88
R_{15} (Palisades) Δ_{15} = 288,370 km.				
13:10:00	355	20:11:40	72700	3.97

propagation distance. Similarly R_1 appears only as a long-period pulse, the propagation distance being too small for any dispersive separation of the component waves. The remaining orders R_7–R_{15} appear only as waves corresponding to the long-period branch, the propagation distances becoming so large as to lose the shorter-period oscillations through their higher absorption.

The new data reaffirm the earlier conclusion[6] that a single dispersion curve represents all the orders and that there is no systematic departure with increasing length of path. It was also concluded in the previous paper that the spectra of the various orders are determined primarily by dispersion, since R_3, R_5, and R_7 cover progressively narrower period ranges entering about 225 sec., the period for minimum group velocity. This was in agreement with the well-known relation between amplitude and the slope of the group velocity curve. It can be seen from table 1 that with

[6] See footnote 1.

increasing order the spectra center on periods from 250 to 350 sec. Apparently the greater selective absorption of the shorter periods becomes an important factor in determining the spectra of the higher order mantle waves.

The relative amplitudes of the higher orders can be used to study the internal friction of mantle rocks. If the decay of amplitude with distance is given[7] by

$$A_z = A_0 e^{-\gamma\Delta}/\Delta^{1/2}$$

where A_0 is constant for a given period and γ is the absorption coefficient, a plot of $ln(A_z \cdot \Delta^{1/2})$ should give a straight line whose slope is γ and intercept is $ln(A_0)$. The average trace amplitudes of R_6, R_7, R_8, R_9, R_{10}, and R_{12} for the period range

TABLE 2

PALISADES AMPLITUDE DATA, NOVEMBER 4, 1952

Order	Δ	A_z	$ln(A_z\Delta^{1/2})$
	deg.	mm.	
R_6	1,004	4.5	4.95
R_8	1,364	2.3	4.45
R_{10}	1,724	1.6	4.20
R_{12}	2,084	1.0	3.80
R_7	1,156	2.0	4.20
R_9	1,516	1.4	4.00
R_{11}	1,876	1.1	3.85

250–350 sec. are listed in table 2. Average amplitudes are given for this period range rather than amplitudes for specific periods in order to minimize the effect of secondary amplitude variations that occur within a train but show no correlation from order to order. These may originate in interferences due to refraction or simultaneous arrival of two orders of mantle waves, both effects becoming more pronounced with the longer propagation paths of the higher order mantle waves.

Reference to table 2 shows that the odd-order mantle Rayleigh waves are consistently smaller in amplitude than the even-order waves. The same phenomenon is apparent on the Pasadena seismogram. Since propagation effects can in no way account for this amplitude variation, it must originate in an asymmetric radiation pattern at the source.

In figure 3 a plot of $ln(A_z \cdot \Delta^{1/2})$ against γ is presented for the period range 250–350 sec. Ordinates corresponding to odd-order waves have been multiplied by a constant factor to allow for the asymmetry of the source. It is seen that points may be represented by a straight line whose slope gives the value $=0.0009$ deg.$^{-1}$ = 0.000008 km.$^{-1}$. From the expression

$$\frac{1}{Q} = \frac{\gamma c T}{\pi}$$

where the phase velocity $C = 4.8$ km/sec. we derive $1/Q = 370 \times 10^{-5}$ as a measure of the internal friction of the mantle in the period range 250–350 sec.

[7] See footnote 1.

Discussion

In figure 2, group velocity data for the Kamchatka shock are presented with those reported previously. For periods less than 400 sec. the two sets of data are in good agreement and serve to determine an empirical dispersion curve with considerable precision. A remarkable property of this curve is the occurrence of a minimum value of group velocity with the dispersion curve well defined by observations at longer and shorter periods

The curve represented by the dashed line in figure 2 is a theoretical curve based on the calculations of Haskell[8] for Rayleigh wave dispersion in a layer having shear

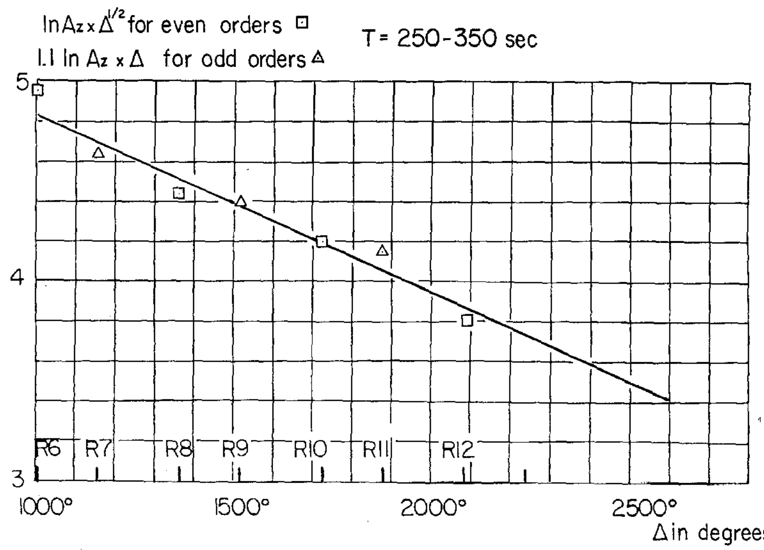

Fig. 3. Graph of logarithm of product of trace amplitude and dispersion factor to obtain absorption constant.

velocity 4.48 km/sec. and thickness 516 km. which overlies a solid half-space having shear velocity 6.15 km/sec. and density 10/9 times that of the surface layer. These constants were selected to make the calculated curve agree with the observed at the minimum value of group velocity. The agreement between the two curves over a significant part of the period range is sufficiently good to indicate that the observed dispersion is controlled by the variation of the shear velocity with depth in the mantle. We view the representation of the mantle by two homogeneous layers as only a first approximation and will undertake in the future to improve the agreement for periods below 200 sec. by inclusion of a better velocity-depth relationship.

For periods greater than 350 sec. the observed group velocities begin to fall far below the theoretical curve. Although more data and further calculations are required to establish this point finally, we attribute the flattening of the group

[8] Norman Haskell, "The Dispersion of Surface Waves in Multilayered Media," *Bull. Seism. Soc. Am.*, 43: 17–34 (1953).

velocity curve to the influence of fluidity of the core. The wave length is about 2,000 km. or about two-thirds of the depth to the core.

Additional instruments which will extend the observations to considerably longer periods will soon be placed in service at Palisades. We expect that the new data will reveal modes of propagation analogous to many of those investigated in our study of wave propagation in a floating ice sheet as modified by the effects of sphericity and gravity.

In the previous paper the investigation of frictional losses in the mantle gave $1/Q = 670 \times 10^{-5}$ for periods of 140 sec. and 215 sec. These correspond to wave lengths of about 600 km. and 1,000 km., respectively. The present value for a period of 300 sec. (average amplitudes over the period range 250 to 350 sec. were actually used) is $1/Q = 370 \times 10^{-5}$, corresponding to a wave length of about 1,500 km., which is proportional and may be taken as roughly equal to the thickness of the outer mantle layer to which this result applies.

Previous measurements of frictional losses have been made for shorter periods—but, as Birch said,[9] these are in need of critical evaluation. They will not be discussed at this time.

Whether the decrease of $1/Q$ from 670×10^{-5} to 370×10^{-5} is due to the dependence of internal friction upon period, or to the dependence upon depth as the longer waves reach greater depths within the mantle, cannot be decided until other types of evidence are used.

LAMONT GEOLOGICAL OBSERVATORY
(COLUMBIA UNIVERSITY)
PALISADES, NEW YORK
Contribution No. 116.

[9] "Handbook of Physical Constants," Geol. Soc. Am., *Spec. Papers*, No. 36 (1942), p. 88.